Department of the Navy
Naval Ordnance Test Station
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"EXPERIMENTS ON STRUTS PIERCING THE WATER SURFACE"

Byrne Perry

Hydrodynamics Laboratory
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Report No. E-55.1

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CONTENTS

ABSTRACT

Water tunnel measurements were made on rectangular bar and circular cylinder struts piercing the free water surface. These were run at several depths and velocities in order to measure drag forces and to investigate the mechanism by which air often ventilates down behind such struts. It was found that the ventilation mechanism depends on viscous wake phenomena in a manner similar to ventilation behind fully-submerged bodies. Moreover, in fully-ventilated flow the forces are well predicted by application of two-dimensional cavity theory. A hysteresis effect on ventilation and forces was observed and found to be caused by surface tension. This last may explain some discrepancies between the present drag data and that previously taken on circular cylinders in a towing tank.

INTRODUCTION

Nearly everyone is familiar to some extent with the features of flow about struts which pierce the surface of a moving stream of water. In general, the water surface is considerably disturbed, a system of waves is set up, and a downstream force is observed. This behavior is also typical, in a larger way, of bridge piers and pilings, or of any body which moves along the air-water interface, including ship and boat hulls, submarine periscopes, and struts such as might be used to support a boat on underwater lifting hydrofoils. Another very similar flow is that which occurs about a torpedo or rocket tail fin during the entry cavity phase. Here the cavity wall is a doubly-curved free surface into which the fin penetrates as the missile yaws or pitches. The resulting force may be sufficient to bend or rip off the fin if it is not properly designed.

The fins used on torpedoes are often rather simple, bluff shapes. It is known that such forms when moving through the water at high speed will usually be followed by a large air-filled region on their aft end, that is to say, they are ventilated. Since previous investigations have not settled entirely the mechanism by which this ventilation occurs, the present experiments have been undertaken to investigate this question, as well as to predict forces on fully-ventilated fins or struts.

EXPERIMENTAL PROCEDURE

The experiments described herein consist of water tunnel force measurements and visual observations on two types of bluff surface-piercing struts, rectangular bars and circular cylinders. Figs. 1, 2, 3, and 4, are photographs of typical test runs. The rectangular bar models are stainless steel stock with leading face 0.1244 in. wide. This face was finished on a shaper and the burrs removed with a file. This was done with care so that the squareness of the machined corners was preserved, because previous experiments with planing surfaces have shown that a very slight rounding may decrease the forces.[1] The dural rods of 0.251 in. and 0.501 in. diameters were sufficiently accurate dimensionally that no further finishing was required.

The Free Surface Water Tunnel working section is 19 in. deep, 20 in. wide, and 8 ft. long and velocities up to 27 fps can be obtained. The tunnel turbulence factor, as measured by sphere tests,[2] is about 1.65 and this leads to a slight roughness of the free surface. The mean position of the surface can be determined with some accuracy but, in any event, the effect of surface irregularity is not big enough to influence the present measurements appreciably so far as determination of the effective submergence is concerned. The tunnel velocity profile has been measured and found to be flat within 0.5 percent, except possibly for the top 1/2 in. of flow. Here the measurement techniques employed at large submergences no longer apply, so that only an estimate can be made, but tracer experiments indicate that the velocity does not drop appreciably. Further information on the characteristics of the tunnel may be found in Refs. 3 and 4.

Velocity measurements were made with the tunnel differential manometer system. This system has been calibrated a number of times against standard pitot tube readings, and is believed to be accurate within better than $\pm$ 1 percent. The velocity manometer is shut off with a valve simultaneously with the taking of force readings, to reduce the error due to slight tunnel velocity fluctuations. The force measurements were taken using the tunnel three-component balance. While all three components were taken, only the drag data was reduced for the present report. The balance is described in Ref. 5.

Previous experience[1,6] with force measurements in the tunnel indicates that data precise to $\pm$ 5 percent are easily obtained with the equipment above, and the present tests are believed to be in this range. Typical force data are shown in Figs. 5, 6, and 7.

MECHANISM OF VENTILATION

It is known that under some circumstances, especially at high speed, the region just aft of a bluff strut will be ventilated by air drawn down from the surface. The air cavity in turn affects the flow and forces on the strut so that the question of whether the strut will or will not ventilate is of some practical importance for high-speed struts. For this reason the present experiments included a considerable amount of visualization of the ventilation process. The following notes are given to help explain qualitatively the nature of the ventilation phenomena.

For a given speed, it is known that the smaller the strut thickness to chord ratio, the less the chance of ventilation. Fine airfoil shapes can be run up to very high speeds without air ventilation and, in fact, it appears that vapor cavitation near the mid-chord point will commence before air ventilates down the aft side.[7] On the other hand, air ventilates down aft of a circular cylinder at very low speeds.

Experiments indicate that the ventilation does not correlate with the potential minimum pressure one might expect on two-dimensional sections, but rather depends more on the way the boundary layer separates from the body. In particular, the nature of the flow in the turbulent wake behind the strut appears to be the prime factor in the mechanism of ventilation. While any body has some sort of wake, it is known that the wake behind a bluff body is especially large. Moreover, it usually contains turbulent, vortex-filled fluid with an average pressure considerably lower than the undisturbed stream pressure, that is, the pressure coefficient C_p is negative. This low wake pressure causes what is known as "base drag".[8] However, while the base pressure coefficient on fully submerged flow changes only slightly with speed, a somewhat different process occurs at the water surface. Here the wake region communicates directly with the atmosphere so that when its pressure is lower than atmospheric, air tends to ventilate into the region. At first this appears only as a few entrapped air bubbles in the wake, sometimes referred to as "boiling" of the wake, but as the speed increases, air displaces the water completely and the region aft of the body consists of an air cavity. The term "cavity" is appropriate because, as will appear shortly, this sort of flow is closely related to cavity flow of the classical type.* Thus, for a bluff body at the surface, the base pressure coefficient, while negative at low speeds, approaches zero for high speed. The base drag is therefore not so severe as would be expected fully submerged, a fact which is utilized in seaplane design in the form of a step, or bluff-ended hull design.

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* It is interesting to note in this connection that the original assumption made by Kirchoff that the drag of a flat plate could be calculated if one assumed the wake was filled with fluid at ambient pressure, although a poor approximation ordinarily, fits in very well to the picture given here.

RELATION OF VENTILATION OF STRUTS TO TWO-DIMENSIONAL CAVITY FLOW

The strut in Fig. 2 is followed by a large air cavity, or region filled with air, that is, it is running fully ventilated. Consider now a horizontal strip of the flow passing through the strut. For a fully ventilated strut, this will appear in plan view as shown in Fig. 8a. The lateral and trailing sides of the bar are not wetted, but are surrounded by air. It is legitimate as a first approximation to regard the flow as two-dimensional so long as the section is not too near the free surface or lower end where the components of vertical velocity are more important. With this assumption, the flow of Fig. 8a is actually a two-dimensional cavity flow of the type occurring behind a flat lamina. This flow and its three-dimensional analogue have been extensively studied both theoretically and experimentally and it will be useful therefore to recapitulate some of the more important results because they are also likely to apply to the strut flow.

It is known, for example, that the so-called cavitation number σ is the most important flow parameter. Here σ is defined as

$$\sigma = \frac{p_{\infty} - p_k}{\frac{1}{2}\rho V^2} \tag{1}$$

where p_{∞} is the pressure in the undisturbed free stream, p_k is the cavity pressure, ρ is the water density and V is the free stream velocity. For the strut flow the cavitation number as defined by Eq. (1) may vary significantly with depth y since $p_{\infty} = \rho g y + p_a$ where g is the acceleration due to gravity, and p_k is equal to the atmospheric pressure p_a for a fully ventilated cavity. Hence Eq. (1) becomes

$$\sigma = \frac{g y}{\frac{1}{2} V^2} \tag{2}$$

which will be recognized as a type of Froude number. Now it is known that the drag force on the body and the shape of its two-dimensional cavity are a function of the cavitation number for a given lamina, and that the cavity dimensions, both length and width increase indefinitely as σ approaches zero.[9] This of course checks well with one's intuitive notion that the air-filled cavity region behind a strut should become bigger as the speed increases.

APPLICATION OF TWO-DIMENSIONAL CAVITY DATA TO STRUT VENTILATION

Returning now the question of whether or not ventilation will occur, one naturally supposes that the measurements on ventilation of such two-dimensional obstacles as rectangular bars might shed some light on the problem at hand. Although these measurements are not too extensive, at least a few conclusions can be drawn. First, it appears that the chief factor in the inception of ventilation in steady flow is the existence of a wake with a general region of stagnant, or more properly, highly turbulent fluid which on the average is stagnant. If, for example, air is forced or bled into the region immediately behind an oblong bar, the flow of Fig. 8(b) occurs, while if the air is put in at the leading corners, Fig. 8(c) shows the flow. It is possible to have two unconnected cavities as in Fig. 8(d), but if the forward cavities become longer, they will join with the aft one as in Fig. 8(a). Even if no aft cavity existed, the forward cavity when permitted to grow by air injection, would eventually envelope the whole bar as in Fig. 8(a). No amount of air injection aft of the bar, however, will cause the flow of Fig. 8(b) to become that of Figs. 8(a) or 8(d). It is possible to cause such a full cavity by some large disturbance to the flow which momentarily causes the cavity to leap forward. This may, for example, be done by passing a large object back and forth in the flow ahead of the bar, so that air can pass forward in its wake. Once started, however, the cavity will be maintained by air supplied anywhere in it. As a further example it is interesting to note that air supplied, say eight or ten widths behind a bar will not start a cavity, because it is too far downstream and the wake has broken up, but if the cavity is once started, and is sufficiently big, the air to maintain it may be supplied to it rather far downstream. To recapitulate, then, the facts seem to indicate that an air cavity can be started by supplying air into a wake region, after which the cavity may grow to many times the size of the initial wake, possible thereby ventilating into other wake regions with further growth. Once the air cavity is established, the air may be supplied at any point within it.

It is worthwhile to mention in passing the state of affairs for smoothly-curved two-dimensional bodies, such as circular cylinders. The situation here seems to be, at least for the cylinder, that air injected in the wake also results in an air cavity considerably larger than the original wake. In contra distinction to the case where there is a sharp corner at which the wake and cavity both start, the point of cavity separation may move upstream from the point of wake separation. The exact mechanism of the flow which determines this behavior, however, is not at present understood. Since the point is a very fundamental one, however, it is under intensive investigation both in hydrodynamics from the point of view of cavity flow, and in hydro- and aerodynamics from the point of view of wake separation. It seems likely that the resolution of these two-dimensional flow questions will have considerable bearing on the understanding of the mechanism of strut ventilation.

AN EFFECT OF SURFACE TENSION ON VENTILATION

In the course of the measurements it was found that at certain speeds it was actually possible to have the strut run either with or without ventilation. Why in one case ventilation occurs and in the other it does not, appears to depend on whether adequate air can be supplied from the air-water surface, since the speed was sufficiently high to cause a cavity if air entered the wake. After some preliminary searching for the difference in air supply, it was discovered that surface tension plays a crucial role in the way the flow behaves. For fully ventilated flow the spray sheets corresponding to the bow wave rise on either side of the bar and spread laterally, as two more or less integral spray sheets with a wide hole in the region just behind the strut. Air continuously passes through this hole, down into the cavity below, where it mixes with the flow at the aft end of the cavity and is carried away downstream.

If, for some reason, the inside edges of these two spray sheets stick together, so to speak, a thin sheet of water in the shape of an elongated blister is formed and the cavity region is sealed off from the outside atmosphere. The air in the cavity under the blister is then quickly entrained and the flow of Fig. 7(b) results. The flow at the surface is somewhat less disturbed, i.e., less splash, waves and other depressions of the surface appear to occur. If the flow is in this unventilated condition, ventilation can usually be started by inserting a stick or other object through the water surface just aft of the strut. On the other hand, the ventilated cavity can sometimes be suppressed by momentarily holding some flat object down on the water surface just aft of the strut, more or less in the fashion of a fairwater running right on the surface.

The above experiments and others strongly indicate that the effect of surface tension can be extremely important in these flows. While much of this difficulty may be eliminated on larger scale struts which have higher Weber numbers, it should be kept in mind that fairly large velocities may be necessary to ensure the breaking up of the spray sheet. Hence the experimenter should be warned to be on the watch for anomalous results which these spray sheets and blisters can cause. The effect on forces, for example, is very appreciable as will be discussed in another section below.

If the effect of surface tension is appreciable, it is important to know which of the two configurations, ventilated or unventilated, will occur in practice. Supposing that the speed is sufficiently high so that ventilation is a possibility, one may reasonably assume that it is more likely to occur than not, since ordinarily the ventilation is harder to stop than to start. For example, if a strut on a hydrofoil boat passes through a wave or the turbulent wake of another boat, the ventilation will surely occur. If the surface is rough or choppy, the ventilation is also more likely. Where ventilation will most likely be suppressed is in perfectly, i.e. almost glassy, smooth water, with the strut starting from rest and accelerating. Further experience will have to be accumulated on these effects before definite answers can be given in practical applications. In the meantime, however, the surface tension in ventilation, especially on small models, should be kept always in mind since it may lead to rather contradictory findings.

ANALYSIS OF FORCE MEASUREMENTS

The series of force measurements for ventilated struts can be conveniently analyzed through the two-dimensional cavity approach outlined above. For example, the drag coefficient on the two-dimensional lamina is known to be

$$C_D = 0.88\,(1+\sigma) \tag{3}$$

Using the value for σ from Eq. (2), one has for a strut running at depth h

$$C_D = 0.88\,(1+\frac{g\,h}{V^2})\,. \tag{4}$$

The average value of σ can be used because Eq. (2) is linear with depth. This analytical result is compared in Fig. 9 with some data on the 1/8 in. wide rectangular bar strut (marked $\theta = 0$) and it can be seen that, with allowances for end effects, the agreement is good.

For the fully ventilating case then, the two-dimensional result seems to give a very good estimate for a flat leading edge. It seems therefore, that the forces on wedge-shaped struts can be similarly estimated. Hence Eq. (4) might be presented in a more general form as

$$C_D = C_{D0}\,(1+\frac{g\,h}{V^2}) \tag{5}$$

where C_{D0} is the two-dimensional drag coefficient for the wedge at $\sigma = 0$. Values for C_{D0} are plotted in Fig. 10 for a range of wedge angles.

EFFECT OF SWEEPING STRUT FORWARD OR BACK

If the strut is not perpendicular to the water surface, that is, if it is swept forward or backward, the two-dimensional approximation used above must be modified because of the strong component of velocity in the vertical direction. It is, however, possible to utilize a theoretical approach commonly used in aeronautics, and previously applied by Bollay[11] to planing surfaces. It is assumed that the flow component parallel to the leading face can be neglected and that all of the force is due to the component normal to the face; this assumption is exact if gravity is negligible and the strut or planing surface is infinitely long. The drag coefficient is then

$$C_D = C_{D2}\cos^2\theta \tag{6}$$

where θ is the angle or sweep from the vertical, either forward or backward, and C_{D2} is the two-dimensional section drag coefficient, for example, $C_{D2} = 0.88$ for a flat leading edge.

While there appears to be no exact method to take into account the effect of gravity, it seems reasonable to assume, as long as gravity is small, that the analysis for the case $\theta = 0$ given above and resulting in Eq. (5) might give a rough first approximation. This replaces the value of C_{D2} of 0.88, which corresponds to $\sigma = 0$, with the more general value

$$C_{D2} = 0.88\,(1 + \sigma)$$

so that Eq. (6) becomes

$$C_D = 0.88\,(1 + \frac{gh}{V^2})\cos^2\theta \qquad (7)$$

In Fig. 9 some experimental data are compared with the value predicted by this equation. The data are evidently in reasonable agreement with the results of the preceding analysis.

In Fig. 11 is shown the effect which surface tension can have on the forces. It should be noted that the force on the strut can be appreciably increased if surface tension does not permit ventilation to occur.

FORCES ON CIRCULAR CYLINDERS

In Figs. 6 and 7 are shown the results of some drag measurements in the Free-Surface Water Tunnel on circular cylinder struts, all without sweep. Also shown are some experimental results obtained in a towing tank by Hay.[12] Before proceeding with a discussion of the present Free-Surface Water Tunnel data, it will be useful to review some of these Princeton results, examples of which are shown in Figs. 12 and 13 as originally given by Hay. This towing tank work appears to have been carried out with painstaking care and in remarkable detail. In Fig. 12 is shown the results of a typical run for a 0.5 in. diameter cylinder. The jump in the curve apparently always occurred at the same speed, that is, no hysteresis effect was reported, and the original drag data shown plotted shows none. This is indeed remarkable since the experience with ventilation obtained here and discussed above for rectangular bars would make one expect a hysteresis of the sort shown in Fig. 11 for the bar. Although no such trend is reported in the Princeton force data, there is some interesting evidence in the photographs in Ref. 12 which indicates that in some instances the strut re-opened a cavity at higher speeds (see Plate 65 of Ref. 12). Also, one certainly would expect some radical change in flow pattern to have occurred at the velocity where the drag jumps, but the photographs in Ref. 12 which correspond to the run shows no such change at this critical velocity.

Returning now to the Free-Surface Water Tunnel data in Figs. 12 and 13, one sees that the Free-Surface Water Tunnel data, all of which was taken for full ventilation, follows a smooth curve, in agreement either with Princeton data or its extrapolation. It is very likely that the towing tank experimenters, starting each run smoothly from rest, were easily able to get the wetted condition, while the tunnel surface roughness and experimental procedure probably favored ventilation. The writer would prefer not to advance any further conjectures, since further experimental work seems more appropriate for clearing up these discrepancies. It is hoped, however, that in future experiments, the peculiar properties of the ventilation phenomenon will be taken into consideration, and that close observation of the flow will be made in the region of sudden drag jumps.

ANALYSIS OF FORCES ON CYLINDERS

The previous analysis for rectangular bars, using a two-dimensional approach can also be applied for the circular cylinder. In this case, the recent work of Armstrong and Tadman shows the drag of a two-dimensional cylinder in a cavity flow to be

$$C_D = 0.50\,(1+\sigma) \tag{8}$$

for σ small. Proceeding now as before to account for sweep, one finds in an analogous manner to that which leads to Eq. (7), that

$$C_D = 0.50\left(1+\frac{gh}{V^2}\right)\cos^2\theta \tag{9}$$

In Fig. 14 the present data for vertical struts of two diameters are shown and, as long as the end effects are kept in mind, one sees that the trends are reasonable. While no data were obtained for values of θ other than $\theta = 0$, it would be of some interest to see if Eq. (9) above would be a reasonable approximation.

CONCLUDING REMARKS

This exploration of the problem of ventilation on surface-piercing struts has indicated that the problem is very closely related to that of initiating and supporting air cavities about completely submerged bodies. Further, the analytical methods used for calculating drag and cavity shape on fully submerged bodies has been modified and applied to some fully ventilated struts with reasonable success. It is believed that the basic mechanism of ventilation will be better understood when more fundamental investigations on fully submerged bodies are completed. In the meantime more experimental data from towing tanks and tunnels, should prove valuable.

ACKNOWLEDGMENTS

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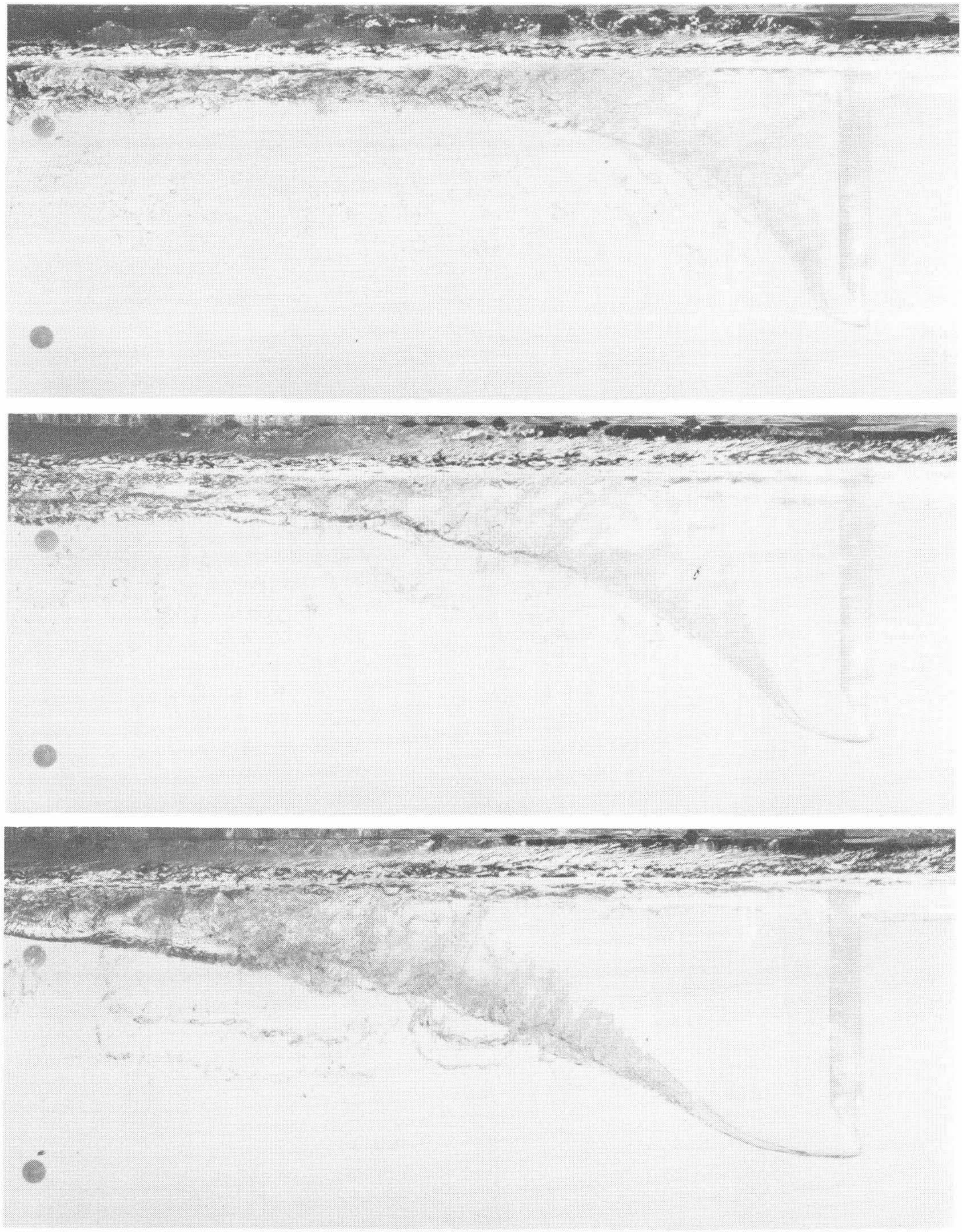

Fig. 1 - Effect of speed on a rectangular bar strut (b = 0. 124 in.) running fully ventilated with air cavity at a submergence of h = 8 in. The flow velocities, from top to bottom, are V = 10 fps, V = 12 fps, and V = 15 fps.

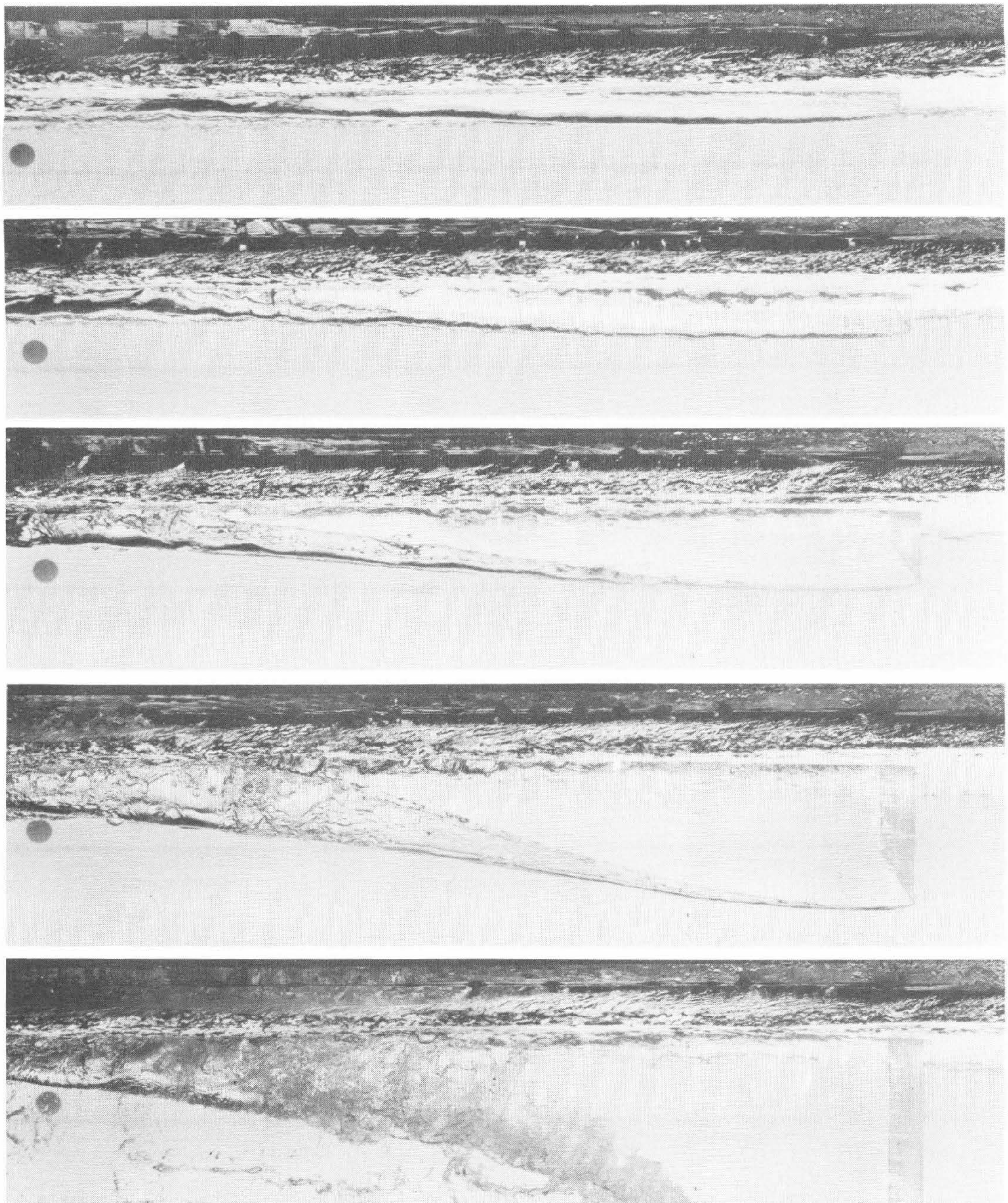

Fig. 2 - Effect of submergence on a rectangular bar strut (b = 0. 124 in.) running fully ventilated at a velocity V = 15 fps. The submergences, from top to bottom, are h = 0. 5 in., h = 1. 0 in., h = 2. 0 in., h = 4. 0 in., and h = 8. 0 in.

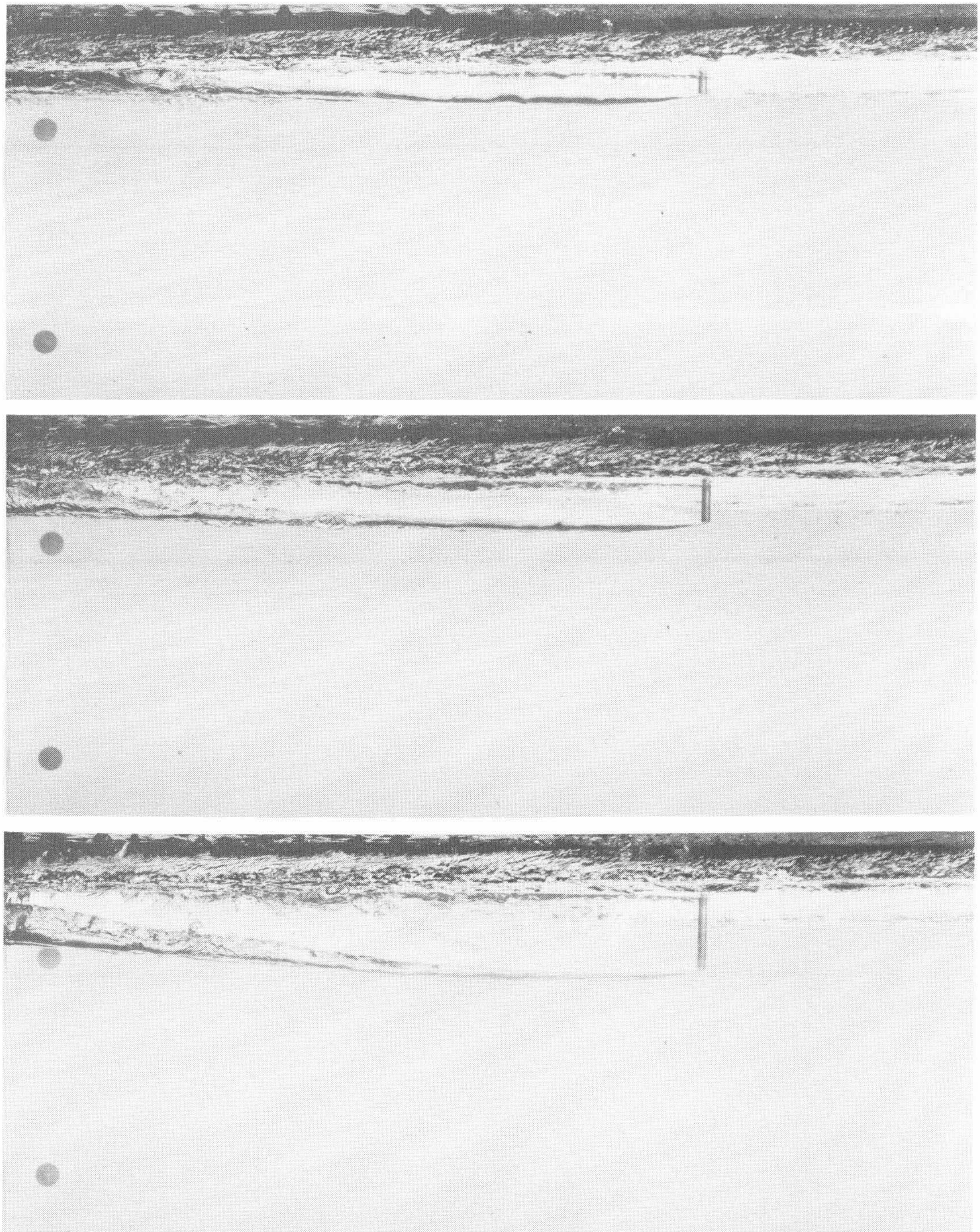

Fig. 3 - Effect of submergence on a circular cylinder strut (d = 0.25 in.) running fully ventilated at a velocity V = 15 fps. The submergences, from top to bottom, are h = 0.5 in., h = 1.0 in., and h = 2.0 in.

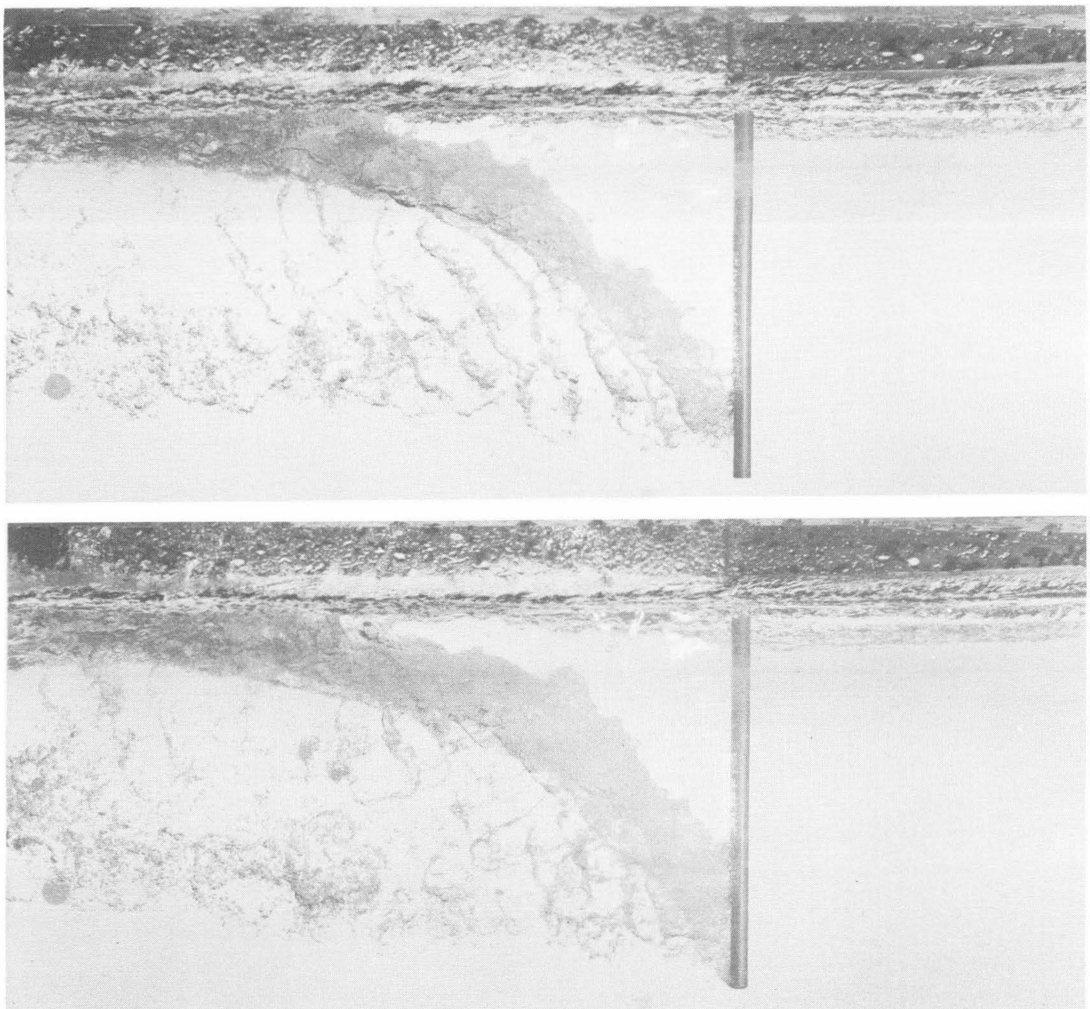

Fig. 4 - Ventilation on a circular cylinder strut (d = 0.50 in.) at a submergence h = 1.0 in. and a velocity V = 12 fps approximately. The flow near the bottom end fluctuates rapidly so that the air sometimes ventilates all the way to the bottom, as shown in the lower photograph.

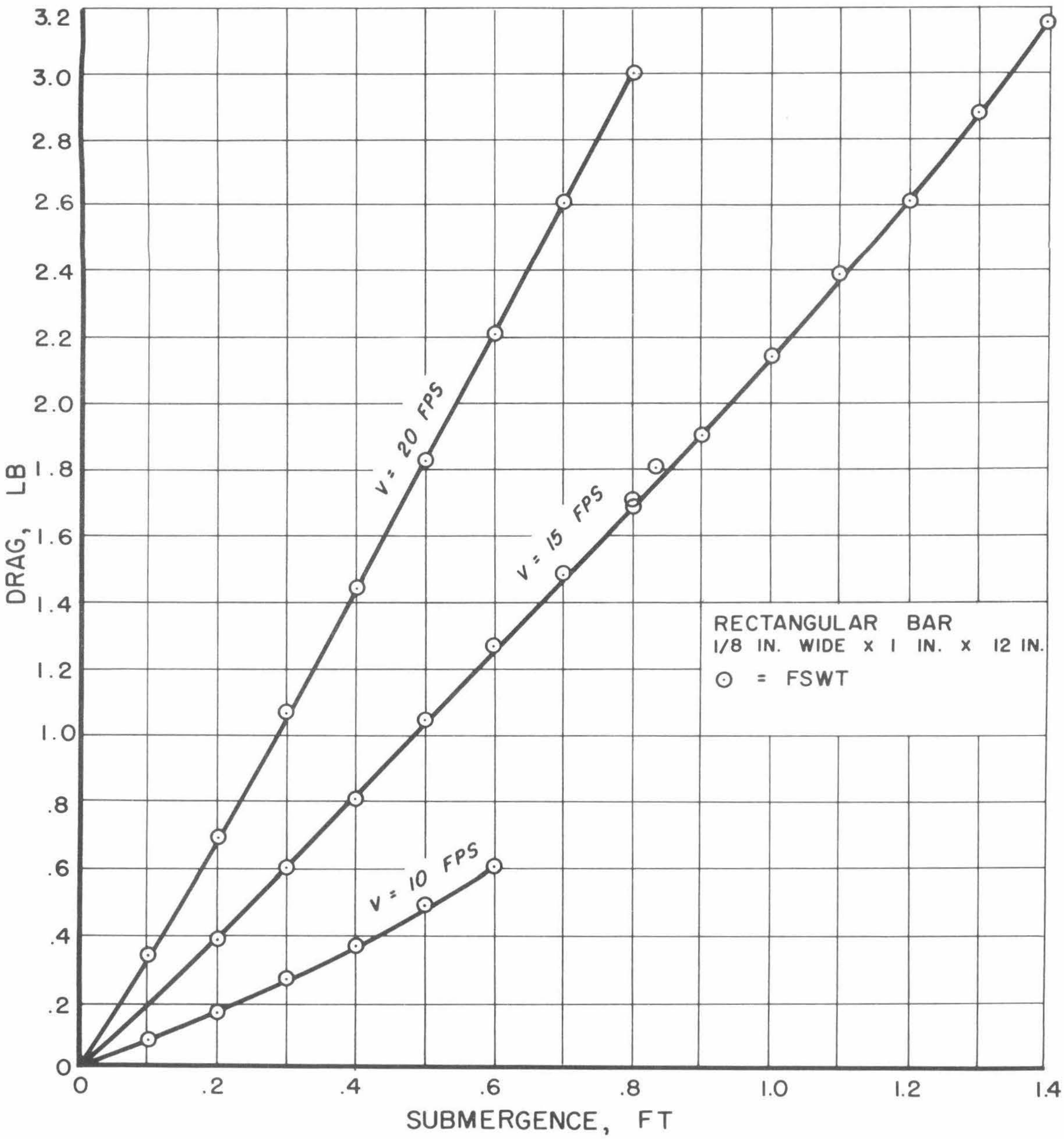

Fig. 5 - Free Surface Water Tunnel (FSWT) drag force measurements on a rectangular bar strut running fully ventilated.

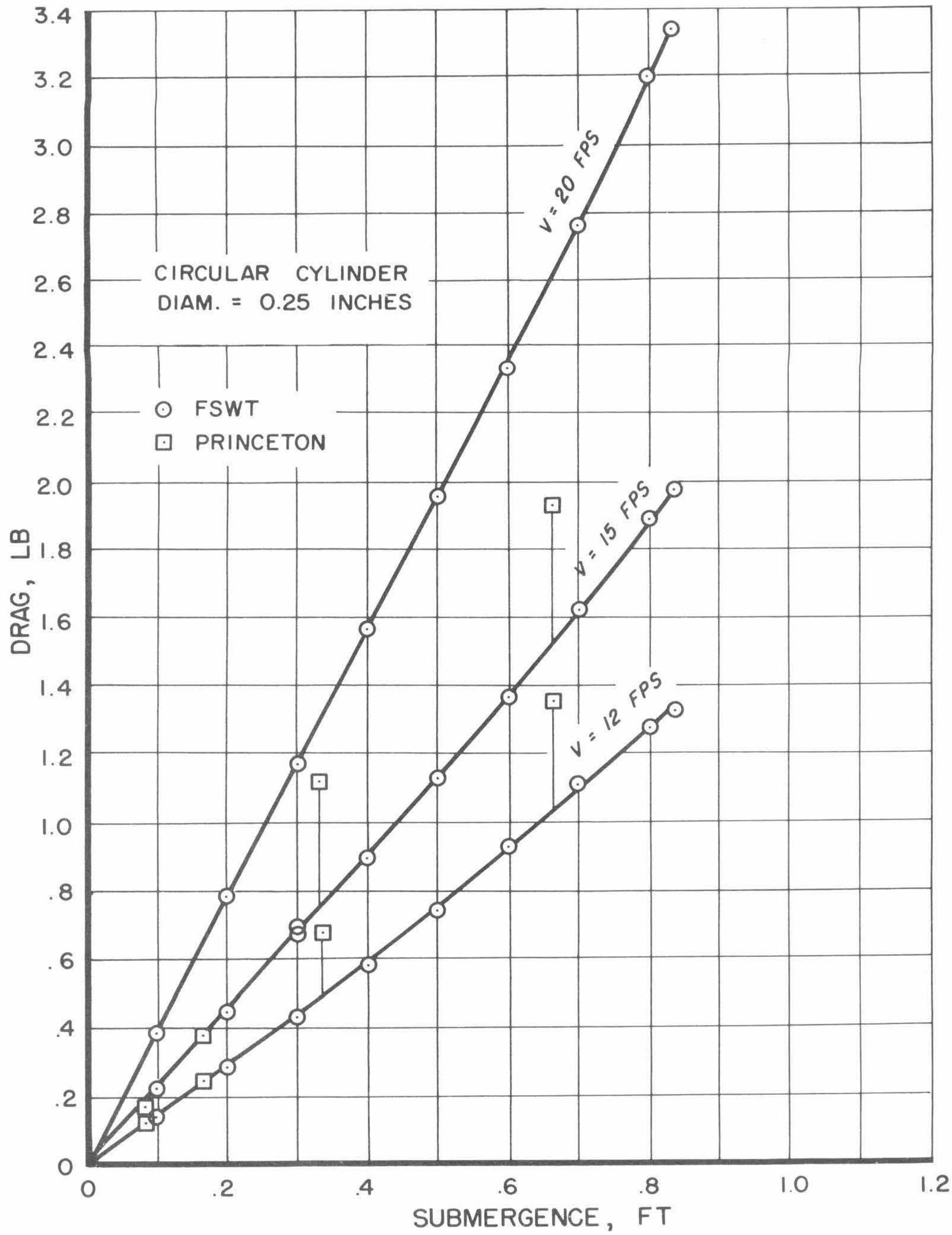

Fig. 6 - Free Surface Water Tunnel (FSWT) drag force measurements on a circular cylinder strut of diameter $d = 0.25$ in. running fully ventilated. It is not known with certainty whether the Princeton data was for ventilated or wetted condition.

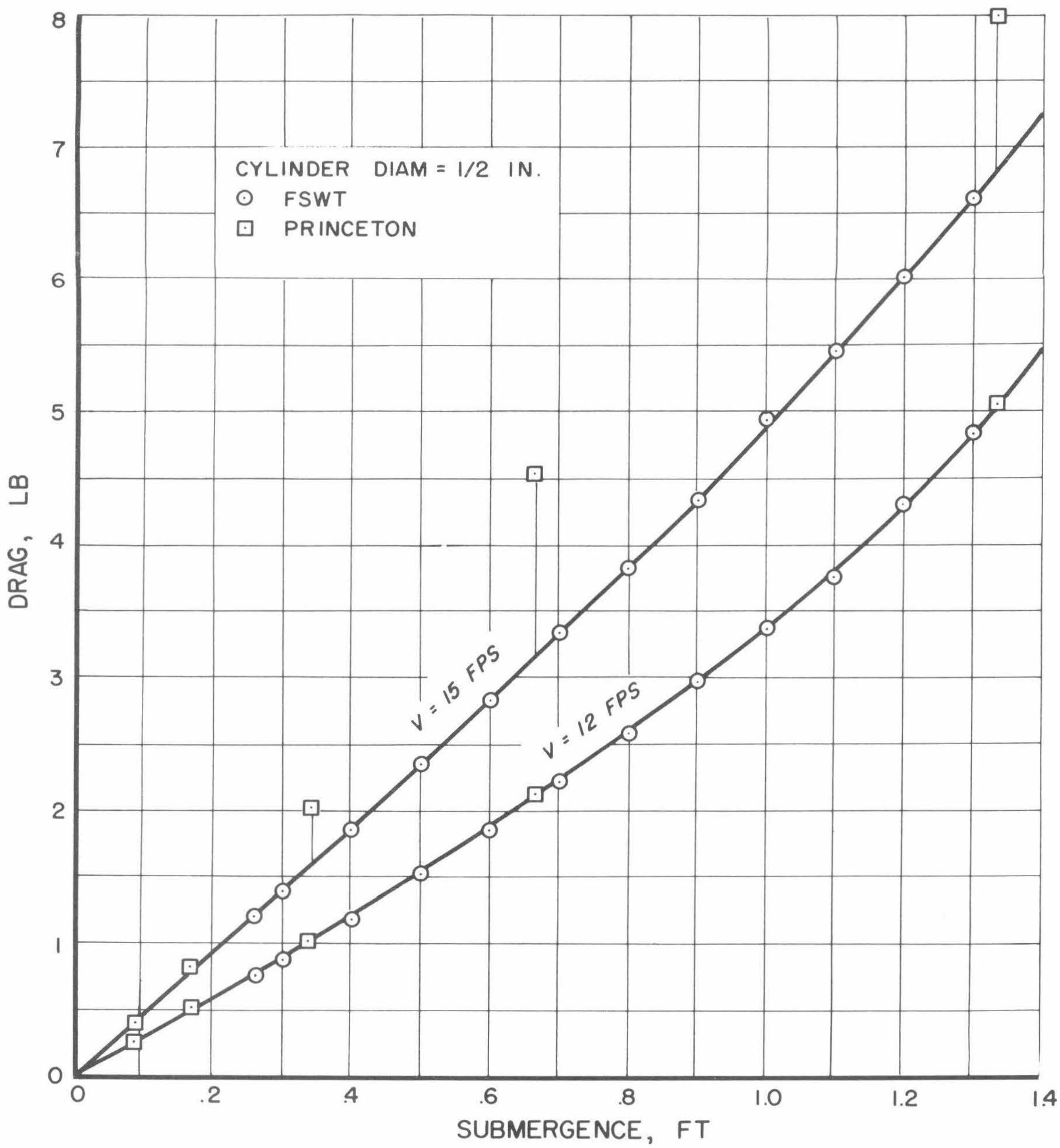

Fig. 7 - Free Surface Water Tunnel (FSWT) drag force measurements on a circular cylinder strut of diameter d = 0.50 in. running fully ventilated. It is not known with certainty whether the Princeton data was for ventilated or wetted condition.

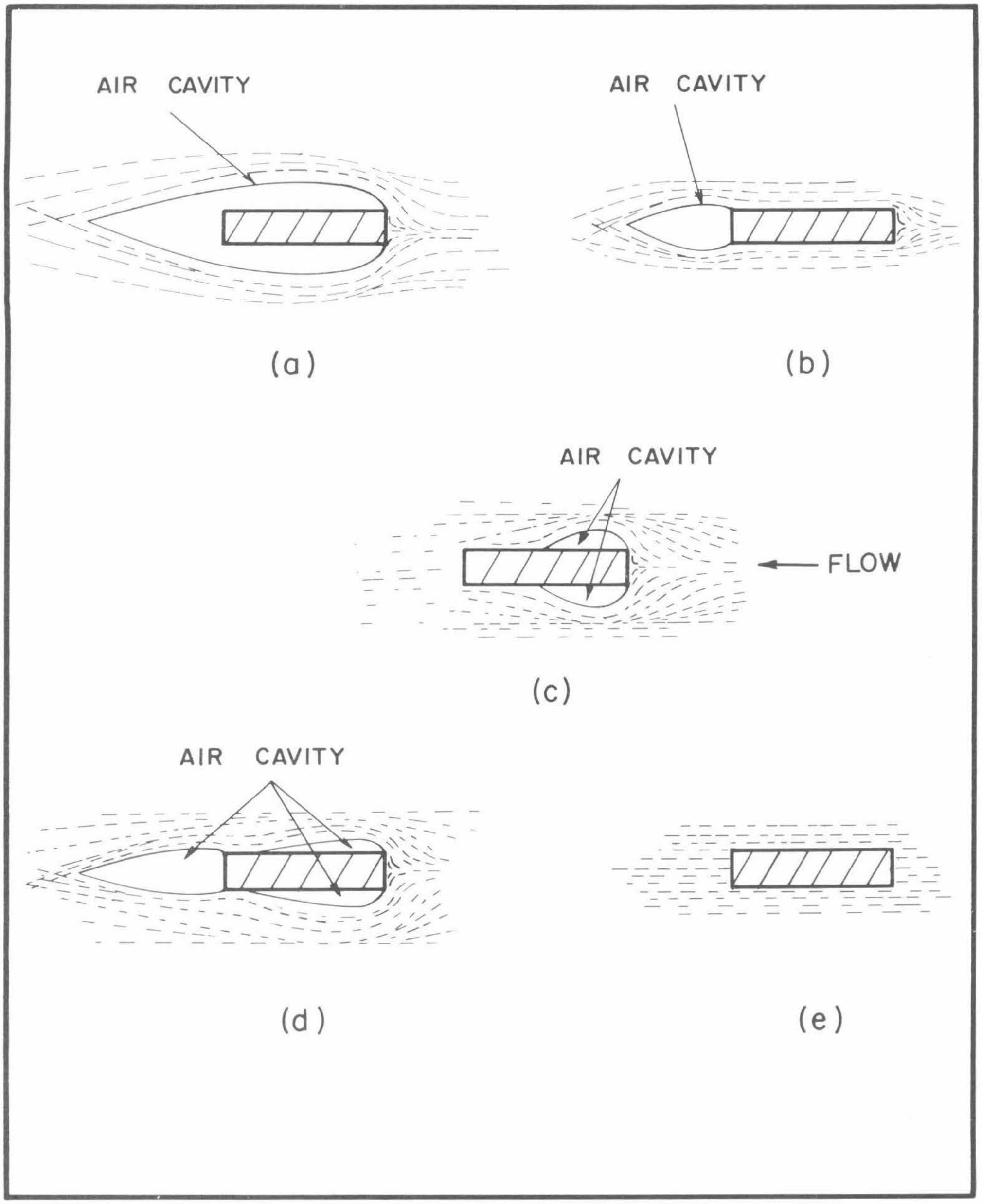

Fig. 8 - Sketches of various two-dimensional flows, showing schematically the possible types of ventilation: (a) fully ventilated; (b) ventilated only at aft end; (c) ventilated only at forward end; (d) combination of (b) and (c); (e) fully wetted.

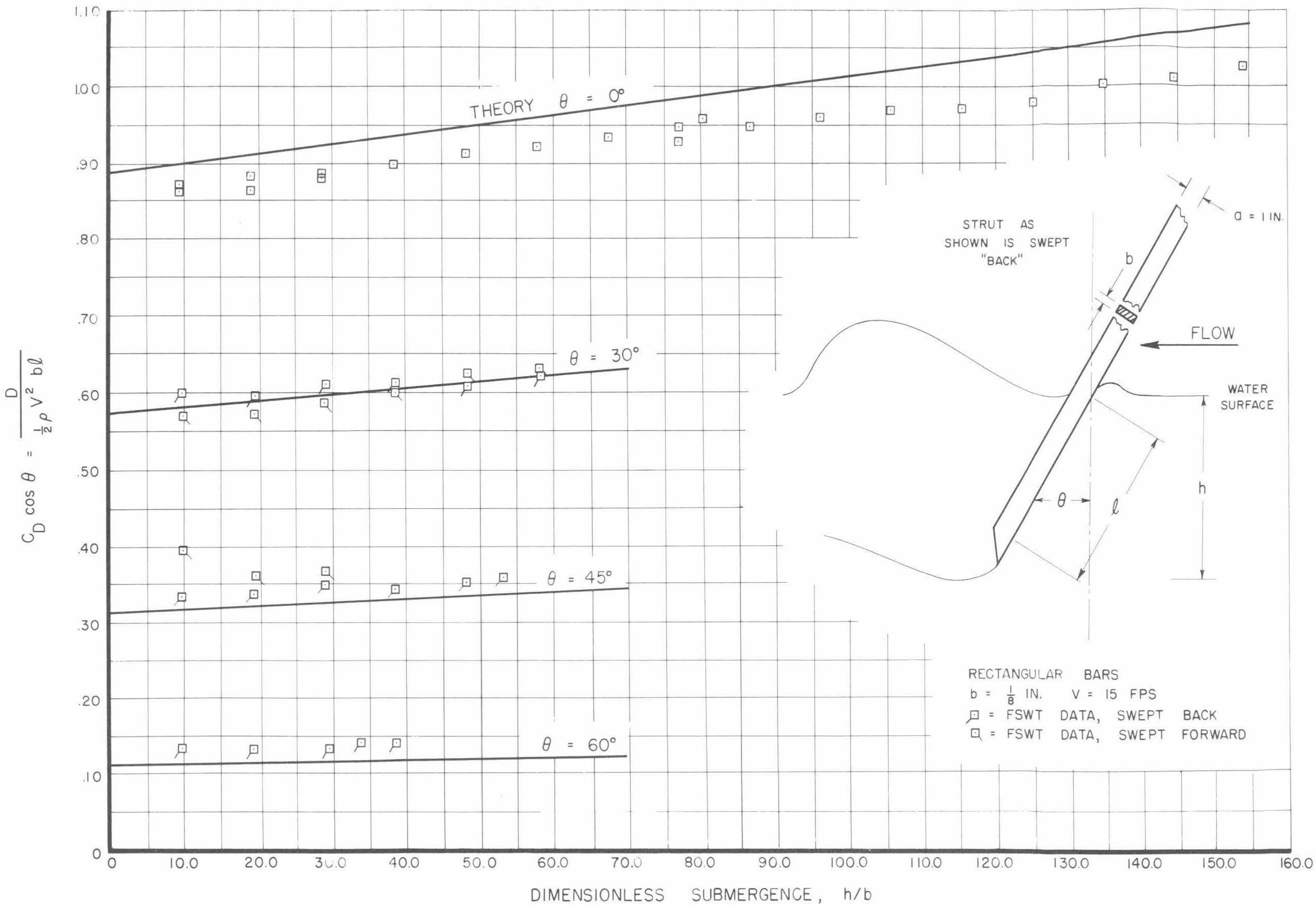

Fig. 9 - Experimental drag coefficients for rectangular bar struts with and without sweep compared with theory of Eq. (7).

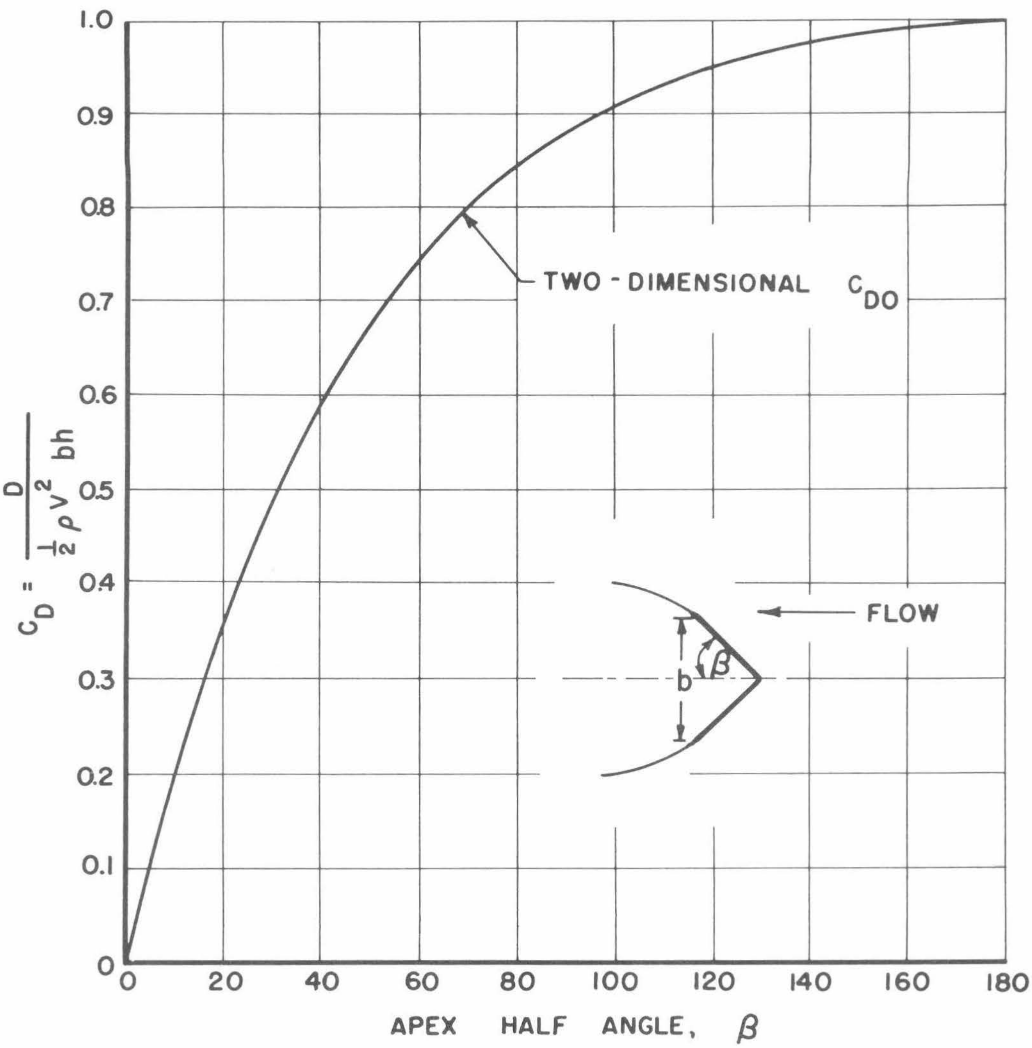

Fig. 10 - Theoretical effect of leading face angle on two-dimensional cavity drag coefficient.

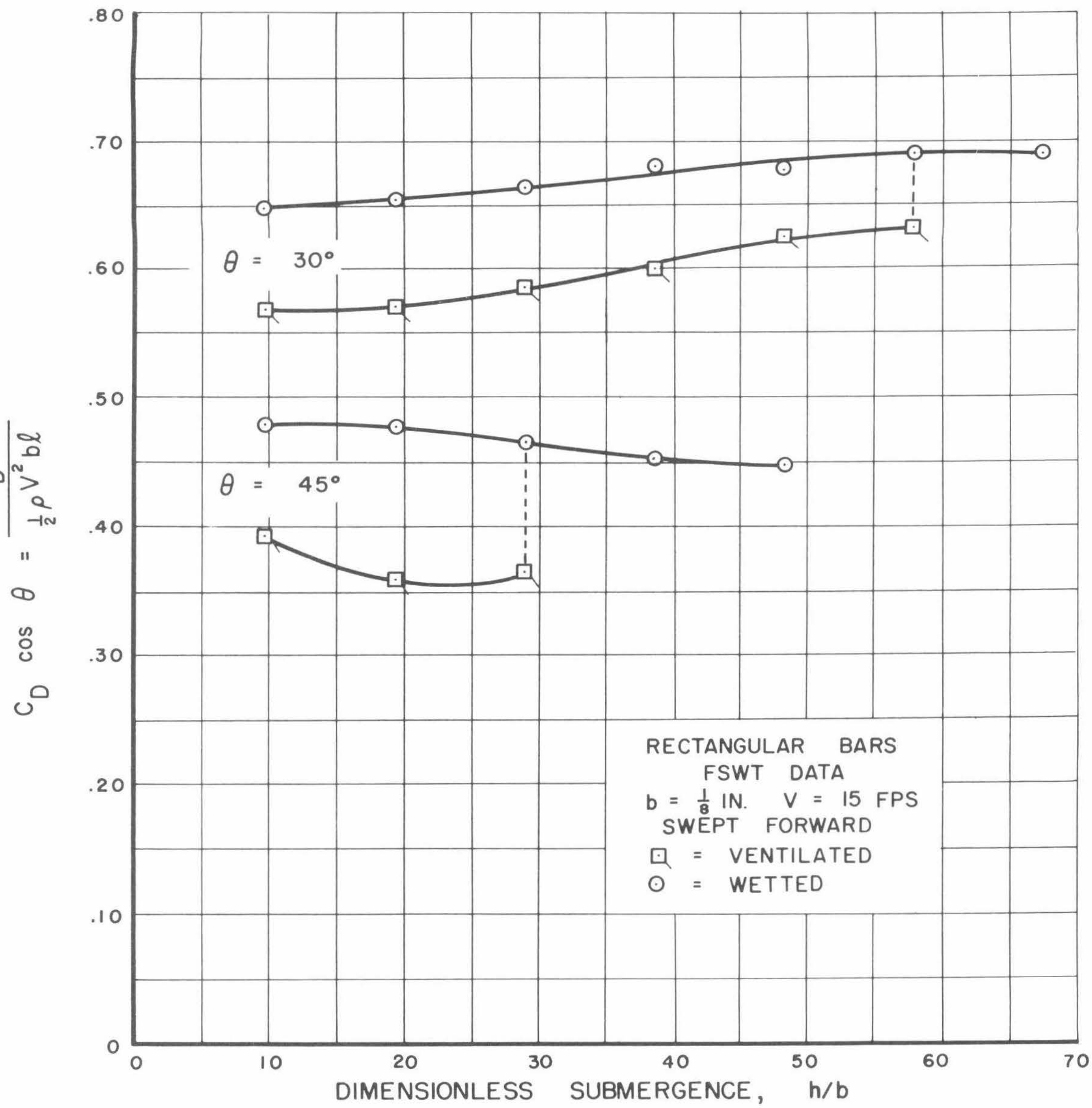

Fig. 11 - The change in drag due to surface tension effect on ventilation.

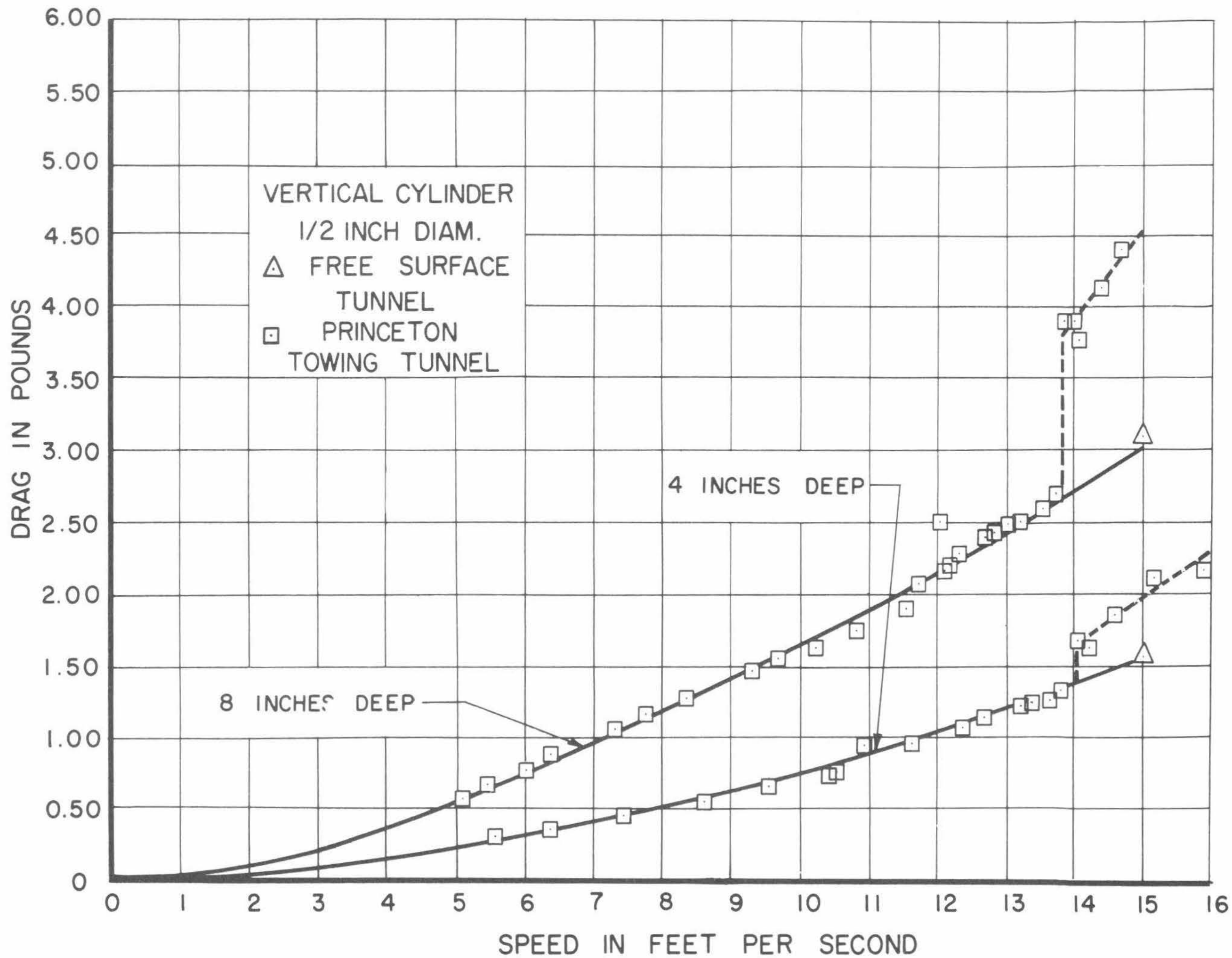

Fig. 12 - Comparison of two sets of measurements of drag force on a circular cylinder. The FSWT runs were all fully ventilated. The abrupt jump in the Princeton drag may be caused by surface tension (see Fig. 11).

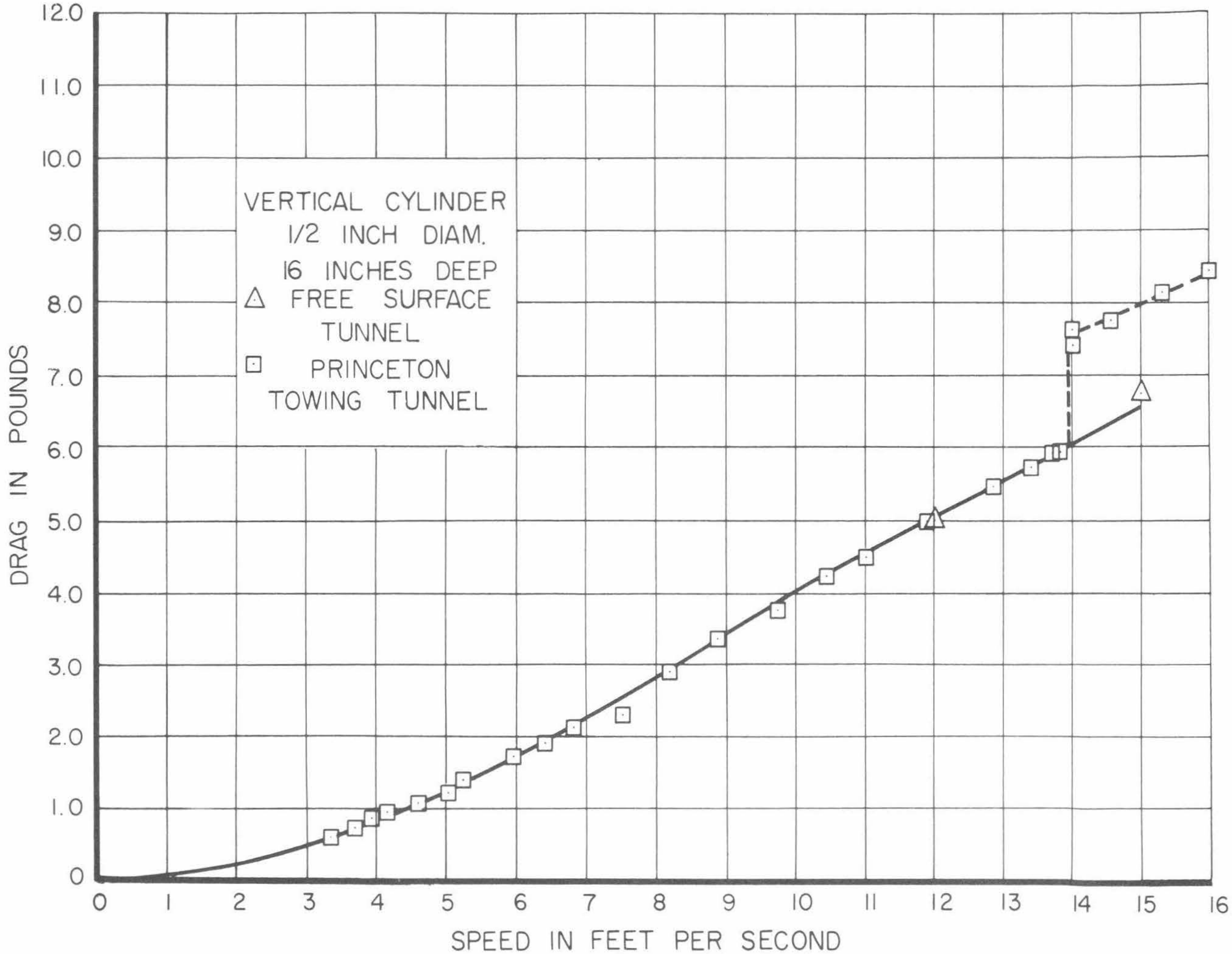

Fig. 13 - Comparison of two sets of measurements of drag force on a circular cylinder. The FSWT runs were all fully ventilated. The abrupt jump in the Princeton drag may be caused by surface tension (see Fig. 11).

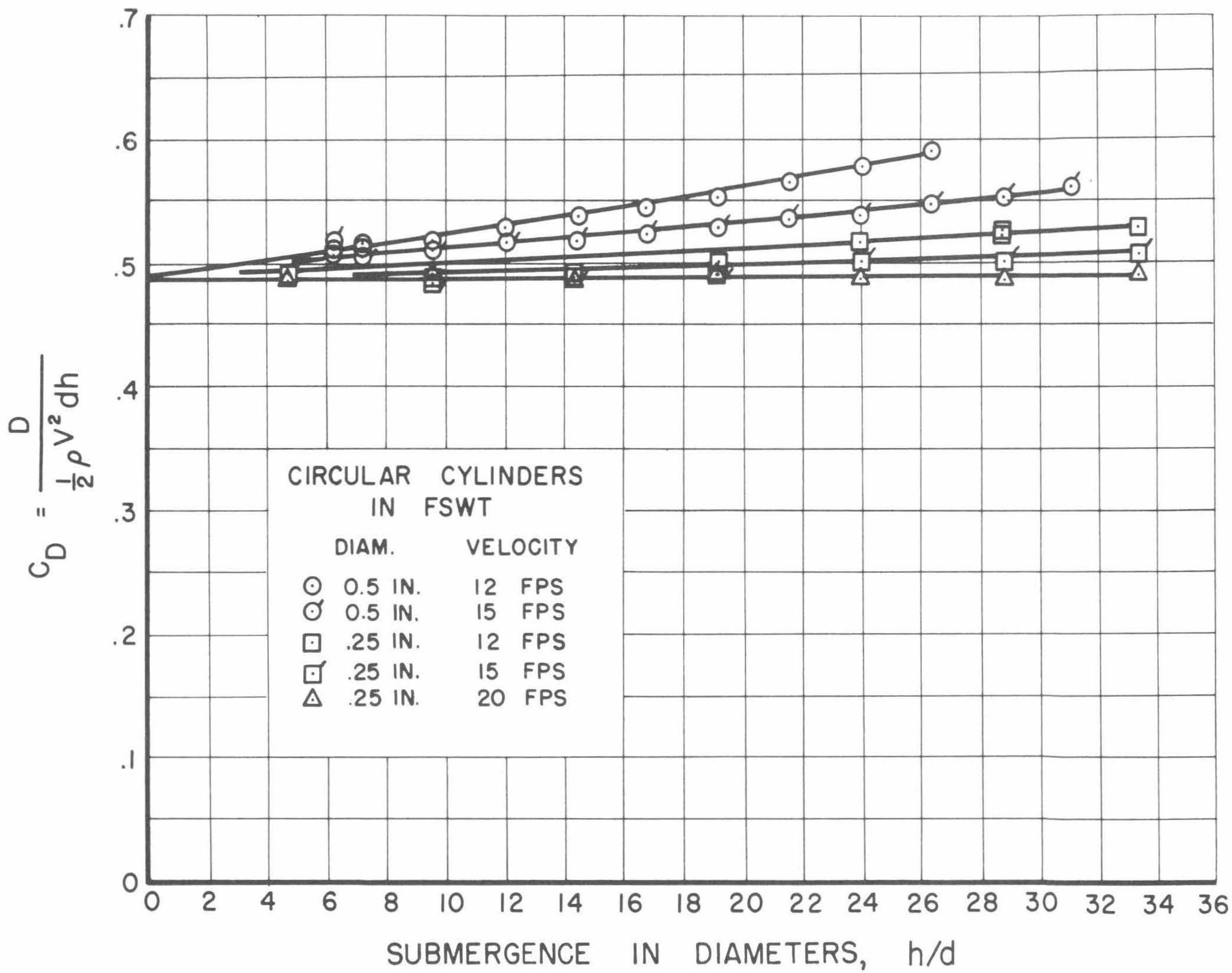

Fig. 14 - Measured drag coefficients for circular cylinder struts running fully ventilated.